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LOAD MODELLING AT LOW VOLTAGE USING CONTINUOUS MEASUREMENTS

Lidija M. Korunović[1], Milica Rašić[1], Nenad Floranović[2], Vladica Aleksić[3]

[1]Faculty of Electronic Engineering, University of Niš
[2]Research and Development Centre "Alfatec"
[3]Public Utility Company "Elektrodistribucija Vranje"

Abstract: *The paper presents the results of load modelling at low voltage level of transformer station (TS) 10/0.4 kV/kV supplying predominantly the residential load. The necessary data is obtained from a recording device and measuring information system for continuous measurements permanently installed in the concerned distribution network. The identified parameters of static exponential load model are classified according to day periods and days of the week, and statistically analysed in order to obtain reliable parameter estimates. These are compared with literature data for the same residential load class. Possibilities for further application of the described load modelling procedure are listed.*

Key words: *load modelling, recording device, exponential load model, parameter estimation*

1. INTRODUCTION

Load modelling is a mature topic, but in the recent years it has again become very challenging and important. Namely, there is a renewed interest in both industry and academia for load modelling, due to the appearance of new types of loads and modern nonlinear electrical and electronic equipment offering increased efficiency and controllability. These are compact fluorescent lamps (CFLs), light-emitted diode (LED) light sources, adjustable speed drives (ASDs), inverter-interfaced distributed generation, plug-in electric vehicle chargers, etc. Furthermore, it is expected that accurate modelling of loads and other network components will be even more important for realising increased flexibility and improved energy efficiency of future electric power networks [1].

There are two general methodologies for load modelling: component based and measurement based approach [2]. The first one assumes a priori knowledge of load models and corresponding load model parameters of individual low voltage (LV) load components. Afterwards, load characteristics at higher voltage levels can be derived from the known load model components and their composition at lower voltages, by applying

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Corresponding author: L. M. Korunović
Faculty of Electronic Engineering, A. Medvedeva 14, 18000 Niš, Republic of Serbia
(e-mail: lidija.korunovic@elfak.ni.ac.rs)

some aggregation method (e.g. [3], [4]). It is very difficult, however, to establish the exact load composition at medium and high voltage levels [5]. The load composition at a bus changes during the year, week and time of the day. Therefore, the results obtained by the component based load aggregation approach should be used with caution, and the measurement based approach regards to be a better one.

The measurement based approach [6]-[10] is based on field measurements at selected electric power system buses, performed specifically for load modelling purposes, or on laboratory measurements of low voltage devices aimed at obtaining their load models. The results obtained for the investigated load buses can be used for modelling the load at other buses if the load structure there is similar. Since load composition changes with time, it is recommended to identify load model parameters for different seasons, different days of the week and characteristic time intervals during a day [11].

Data for load modelling using field measurements can be obtained from field tests or from continuous measurements. The field tests are allowed to be performed in time periods when they cannot endanger electric power system operation. During these tests operating conditions have to be within acceptable, predefined limits, that sustains safety and the quality of the supply. Therefore, the ranges of the voltage changes during the tests are rather narrow [11], [12]. Continuous measurements imply data recording by the equipment with a relatively large memory in time intervals when the disturbances in electric power system occur [13]. Some of these recording devices can transmit or process the data [12].

The measurement based approach requires permission of electrical distribution company and relatively expensive measuring equipment. It becomes very difficult to get the permission for the field test in electric power system in the environment of electric energy deregulated market and generally in the market economy. Additionally, the engagement of utility's employers is needed. Therefore, continuous measurements are much more promising, especially in a smart grid environment.

The idea of this paper is to present the procedure of load modelling using pre-installed recording equipment for continuous measurements in a distribution network. Thus, there is no additional cost for the purchase and installation of generally very expensive measuring equipment. Since new types of recording devices can transmit data to the control centre, getting permission for every entrance into utility's substations that was necessary for local access to data stored in older types of devices, is avoided.

In general, the procedure is applicable to all voltage levels. It is demonstrated in the paper on the example of the low voltage aggregate load. It is of an additional importance, since there is no published research that deals with load modelling using measurement based approach at low voltage. The main reasons are: necessity of the usage of very expensive recording equipment, large number of load buses at LV and stochastic nature of aggregate load at these buses that disturb the identification of load model parameters. The final aim of this paper is to approve the ability to obtain statistically reliable parameters of the load at LV in different days of the week and in different day periods.

2. DATA RECORDING, STORING AND TRANSMISSION

In the Public Utility Company "Elektrodistribucija Vranje" several recording devices have been installed at low voltage level of TSs 10/0.4 kV/kV in order to measure the load consumption that enables comparison of the delivered and consumed energy and to find possible causes of the increased energy losses. Technical capabilities of such a device as an embedded part of the measuring information system (MIS) [14] are discussed briefly in this paper. These are: measuring, recording, storing and transmission of recorded data.

The MKS–I2–5 device type has been installed in TS "Asambair krug" 10/0.4 kV/kV that supplies predominantly the residential load (households count 92.3 % of all 349 LV consumers in this consumption area). This transformer station is the first one of three TS 10/0.4 kV/kV fed by the same 10 kV feeder. The feeder is supplied from TS "Vranje 1" 35/10 kV/kV located in the urban area of town Vranje that is fed by TS 110/35 kV/kV including two on-load tap-changing transformers (2×31.5MVA, 110±10×1,5%/36,75/10,5 kV/kV/kV). The simplified one-line diagram of the device connections in TS "Asambair krug" is depicted in Fig. 1. Current probes of the device are connected to the transformer secondary via the existing current measuring transformers (CT), and voltage probes are connected to LV bus directly.

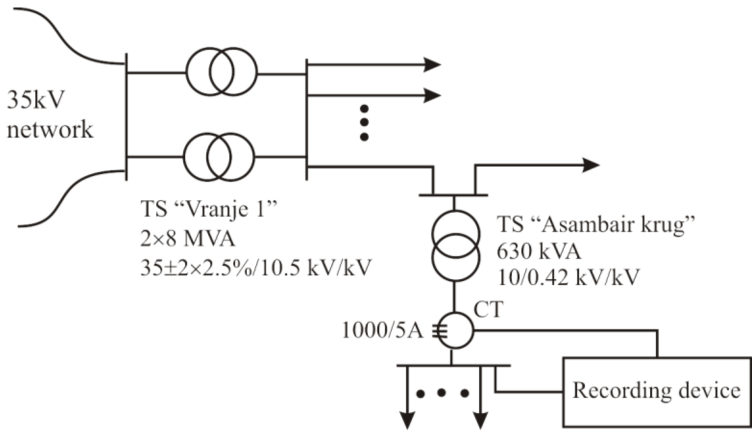

Fig. 1 Principal diagram of device connections in considered TS

Currents and voltages are recorded and processed by MIS. It can store significant number of variables such as: true effective (rms) current values, phase and phase-to-phase rms voltages, single-phase and three-phase real, reactive and apparent power, individual and total harmonic distortions of particular currents and voltages, etc. Variables to be stored, as well as the sampling rate, depend on user settings. The recorded data is stored on 14 GB HDD disk of the device.

The stored data can be accessed locally by the implemented device functionality using a USB memory stick and using a GUI (Graphical User Interface) of the device. The data is automatically transferred to the USB memory stick after the hardware is connected via the USB port, i.e. software module is activated and the data is transferred. Another way of local access to the stored data is by Ethernet using a cross over cable, SSH (Secure Shell) protocol of the suitable SSH client. The data can be also accessed remotely in the Control centre of the Public Utility Company "Elektrodistribucija Vranje". The data transmission to the Control centre is performed automatically by execution of the pre-set scripts over GSM/GPRS communication channel or a digital radio modem, with the transfer speed of

200 kB/s and 9.6 kB/s, respectively. In both cases, the stored data is accessed using a SSH client, which is a software program that incorporates the SSH protocol for the connection to a remote computer.

The central server located in the Control centre storages recorded MIS data which can be further processed, analysed and used for exploitation and planning purposes. Since rms voltages and real and reactive power recorded by the device are required for load modelling, they can be used for this issue. The application of the pre-installed MIS and data stored by the central server, in the domain of load modelling, is demonstrated bellow.

3. Operation Data

The period of ten days of normal distribution network operation is chosen for the analysis. The device recorded data from 1st to 10th March 2012 with the sampling period of 12 s, according to the pre-defined setting of time-interval for the monitored parameters of energy consumption in the considered consumption area. The recording device generates a special file format optimized for the data transfer with high compress compatibility. The average size of one day file is 400 kB, with the resulting total size of the uncompressed file for ten day period of 4 MB. Therefore, it is easy to transmit, store and process the recorded data for the discussed period, but also for longer time intervals, e.g. several months or year(s). Furthermore, it is expected that the number of recording devices in distribution network(s) in the future will increase and enable simultaneous data collection from various consumption areas of different TSs. This will facilitate a widespread application of the proposed load modelling procedure. In the considered LV distribution network the number of remotely accessed devices is limited only by the provider capacity in the case of GSM/GPRS communication channel, i.e. by the capacity of the subnet protocol of the provider. In the case of digital radio modem transmission, limitations are: line of sight between the two transmitting antennas, bandwidth and transmitter signal strength.

Figs. 2a), 2b) and 2c) present voltage, real and reactive power curves recorded in TS "Asambair krug" on Sunday, 4th March, and Figs. 2d), 2e) and 2f) the corresponding curves recorded on Friday, 9th March. General observations that will be listed for these curves refer also to the corresponding curves for other days. The voltage changes in the relatively narrow ranges from its maximum value of 417.3 V and 417.4 V on Sunday and Friday, respectively, measured during early morning hours in the period of low load, to the minimum values: somewhat greater than 396.5 V in the period of high evening load on Sunday, and 391.9 V around 10 am on Friday. Real power curves are characterized by the decreases during the night, their minimum values (174.9 kW and 187.4 kW on Sunday and Friday, respectively) in the early morning, followed by the increases up to the late morning hours when they start to vary in narrow ranges. There are the trends of load increases from early evening hours up to 594.4 kW at 19:38:08 pm on Sunday and up to 549.2 kW on Friday at 20:00:15 pm. Both real power curves decrease before the midnight. These curves are also characterized by stochastic load changes. Stochastic rapid changes are more notable in reactive power curves. Minimum values of these curves are 42.6 kVAr and 39.6 kVAr, on Sunday and Friday, respectively, and corresponding maximum values are 103.4 kVAr and 113.6 kVAr. The challenge is to identify load model parameters under such stochastic nature of the load typical for LV networks.

It should be emphasized that the trends of voltage curves and numerous small changes of the voltage are not predominantly influenced by the supplied load, but rather by the rest of the electric power network and the voltage regulation at higher voltage levels. In the presented load modelling procedure only abrupt voltage changes greater than 1.5 % of the rated voltage (U_n), are selected for the analysis. The changes that are less than 1.5 % of U_n cause very small real and reactive power changes strongly influenced by stochastic load variations. These variations significantly disturb the identification of load model parameters.

The analysis of the curve from Fig. 2a) reveals that only two abrupt voltage changes greater than 1.5 % occurred during Sunday. At 02:01:38 am the voltage decreased approximately from 414 V to 405 V (i.e. for nearly 2.3 % of U_n) and immediately after that increased to approximately the same value. Similar abrupt voltage changes are typical for early morning hours, and these are also recorded on Friday (Fig. 2d)). The considered LV network and supplying medium voltage network do not include controlled capacitors or other regulating equipment that are adjusted to operate when voltage changes or voltage values are beyond the predefined limits. Therefore, it can be concluded that the described variations are the result of voltage regulation performed by changing the tap position of on-load tap-changing transformers in TS 110/35 kV/kV that both supply TS "Vranje 1".

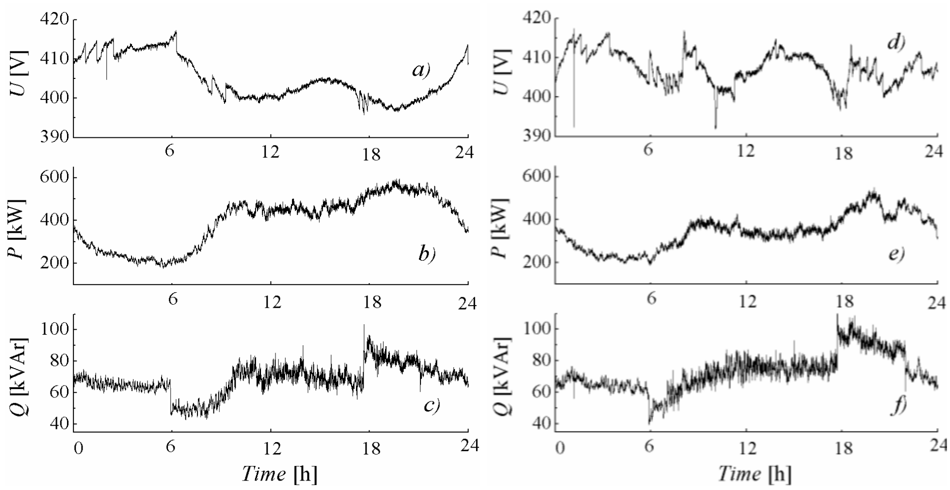

Fig. 2 Voltage a), real b) and reactive power c) curves during Sunday, and voltage d), real e) and reactive power f) curves recorded on Friday

Fig. 3 zooms two voltage changes (and corresponding real and reactive power responses) that started at 1:09:36 on Friday, 9th March. These are voltage decrease and voltage increase for approximately 6 % of U_n. Time in this figure is labelled with integers - zero denotes the recording moment when the first change started, and two negative and four positive numbers correspond to two prior and four subsequent recording moments, respectively. Stochastic changes of the real and reactive power when the voltage is almost constant are notable in Figs. 3b) and 3c), respectively. The identified load parameters under presence of such stochastic load variations should be accepted with caution. Therefore, load modelling procedure presented in this paper includes the analysis of a large number of voltage changes and statistical analysis of identified load model parameters in order to obtain estimated, but reliable parameters.

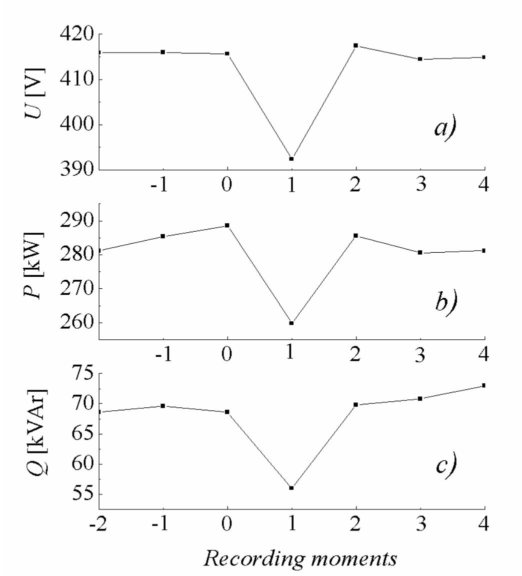

Fig. 3 Two subsequent voltage changes a), and real b) and reactive c) power responses

4. Load Model

Both voltage changes in Fig. 3 are depicted by two points. Voltage decreases and the corresponding real and reactive power responses start at the recording moment 0 (point 0) and finish at moment 1 (point 1), while voltage increases and its immediate power responses start at moment 1 and finish at the recording moment 2. Therefore, very simple load model can be used, such as exponential load model with frequency dependence term neglected (since the voltage changes much more than frequency). It is one of the most frequently used static load models [1]:

$$P = P_n \left(\frac{U}{U_n} \right)^{k_{pu}}, \tag{1}$$

$$Q = Q_n \left(\frac{U}{U_n} \right)^{k_{qu}}. \tag{2}$$

In model (1)-(2) P and Q denote real and reactive load power at voltage U, P_n and Q_n are real and reactive load power at the rated voltage, k_{pu} and k_{qu} denote parameters of the model, voltage exponent of the real and reactive power, respectively. If both voltage exponents are 0, 1 or 2, the load is of constant power, current or impedance type, respectively. There is the variant of model (1)-(2) with the initial real and reactive power values, P_0 and Q_0, at the initial voltage U_0, instead of P_n and Q_n at U_n [2].

The exponential load model describes the changes of the real and reactive power of predominantly residential load with voltage variations in the range from 0.915 pu to 1.1 pu, with acceptable mistakes [7]. These mistakes are up to 1.1 % for real and 6 % for reactive power. The analysis of all abrupt voltage changes during the concerned period of ten days shows that the voltage belongs to a relatively small range during all 42 changes, i.e. from 417.4 V (≈1.044 pu) to 377.6 V (0.944 pu). Therefore, exponential load model is adequate.

The parameters of the variant of the exponential load model, that includes initial voltage and power values, can be calculated as:

$$k_{pu} = \ln\left(\frac{P}{P_0}\right) \Big/ \ln\left(\frac{U}{U_0}\right) \approx \frac{(P-P)/P_0}{(U-U_0)/U_0}\,, \tag{3}$$

$$k_{qu} = \ln\left(\frac{Q}{Q_0}\right) \Big/ \ln\left(\frac{U}{U_0}\right) \approx \frac{(Q-Q_0)/Q_0}{(U-U_0)/U_0}\,, \tag{4}$$

for small voltage (and therefore small power) deviations. According to (3) and data from Fig. 3, k_{pu}=1.778 and k_{pu}=1.554 are identified for voltage decrease and increase, respectively. Analogously, k_{qu}=3.272 and k_{qu}=3.853 are obtained for the data from the same figure using (4).

More precise results of load modelling can be obtained by the increase of the sampling rate, by carrying out filtering [1] and/or by the selection polynomial load model that is proved to be more accurate [10]. However, the main aim of the paper is to demonstrate that it is possible to use small files of the recorded data and to obtain reliable model parameters. Namely, the utilities in Serbia very often meet problems of the transmission of large data files. If the sampling rate is increased, such kind of files will be obtained by the measurements at numerous LV buses in long periods of time (that is the final aim of the research whose beginning is presented in this paper).

5. Parameter Estimation

The further analysis of the recorded voltage values revealed that 42 voltage changes, greater than 1.5 % of U_n, occurred during the ten considered days, while the maximum recorded change was 7.6 %. The data is separated in two sets. The first set is used for model tuning and it includes data from 1st March to 3 pm of 7th March, with 28 voltage changes. Another data set is used for model verification. It includes data from 3 pm of 7th March to 10th March, with 14 recorded voltage changes. Table 1 lists the number of the considered voltage changes from the first data set that are grouped according to different time intervals of the day and three characteristic days of the week – working day, Saturday and Sunday. In the majority of time intervals and on both working days and weekend days, voltage changes greater than 1.5 % were recorded and the corresponding load model parameter was obtained.

Table 1 Number of voltage changes in time intervals and days of the week

Time interval [h]	Number of changes	Day of the week	Number of changes
0–6	10	Working day	32
6–12	4		
12–18	14	Saturday	4
18–24	0	Sunday	2

The identified parameters are also grouped according to time intervals and days of the week, and statistically analysed. The results of this analysis are mean values and standard deviations of the parameters of three time intervals and days (Table 2). Mean, i.e. estimated value of k_{pu} is the smallest in the afternoon, from 12 h to18 h (k_{pu}=1.382), and it is the largest in the morning, from 6 h to 12 h ($k_{pu}\approx 2$). It can be explained by the changes in load composition during the day, indicating that the resistive load devices are predominant load component in the morning hours. Parameter k_{pu} of the resistive load devices is 2, as listed in numerous papers and books such as [2, 3, 7]. stimated value of k_{pu} in different days of the week, and therefore average load composition, is almost the same. This parameter belongs to the narrow range, from 1.561 to 1.662.

Standard deviation of k_{pu} is the measure of parameter dispersion. This standard deviation belongs to a relatively wide range, from 0.055 for Sunday to 0.958 for the period 12-18 h. Greater values indicate that load composition changes significantly in the considered time intervals or days, but also this can be caused by larger stochastic load changes. Thus, the analysis of small voltage variations, in the range from 1 % to 1.5 % of U_n, in the time interval 18-24 h and their real power responses yields: mean value of k_{pu} is 2.017 and the corresponding standard deviation is of the order of mean value (it is 1.681). Such So large standard deviation confirms the statement from Section 3 - parameters obtained on the basis of such small voltage changes are very unreliable.

Table 2 Mean values and standard deviations of the parameters

Parameter	Time interval [h]	Mean	Standard deviation	Day of the week	Mean	Standard deviation
k_{pu}	0–6	1.874	0.498	Working day	1.662	0.831
	6–12	2.013	0.958	Saturday	1.561	0.308
	12–18	1.382	0.774	Sunday	1.608	0.055
k_{qu}	0–6	3.659	0.784	Working day	2.998	0.603
	6–12	2.449	0.163	Saturday	3.916	1.264
	12–18	3.023	0.637	Sunday	3.550	0.255

Mean, i.e. the estimated value of k_{qu} grouped according to the time intervals changes from 2.449 in the period 6-12 h to 3.659 in the early morning hours (0-6 h). According to small voltage deviations 1-1.5 % of U_n, the mean value of k_{qu} is 4.301 in the interval from 18 h to 24 h, but again the standard deviation is almost equal to the mean value, it is 4.039. Mean values of k_{qu} that are grouped according to the days of the week belong to a somewhat narrower range, from 2.998 during working days to 3.916 on Sunday, confirming that that the load composition vary rather with day periods than with the days of the week. Standard deviations of k_{qu} are several times smaller than the corresponding mean values.

Mean values of parameters from Table 2 represent load behaviour during 28 examined voltage changes very well. It is proved by simulations of both real and reactive power responses to these voltage changes by the exponential model with the corresponding mean values of parameters from Table 2. When parameters of time intervals are used, in only three of 56 simulations the errors are greater than 5 %, while the largest error is 6.8 %. Similarly, simulations that assume estimated parameters for the corresponding days of the week cause the error that is beyond the acceptable limit of 5 % in four cases (i.e. in approximately 7% of 56 simulations).

Furthermore, the estimated, mean parameters are validated on the second set of the recorded data. This set includes four voltage changes in the time interval 0-6 h and ten changes in the time interval 12-18 h, both on working days. Very small deviations from the measured values are obtained. When parameters of particular time intervals are used, they do not exceed 6.6 % and in about 10 % of cases deviations are greater than 5 %. Similarly, in approximately 7 % of cases the errors are greater than 5% when the mean values for a working day are used. It indicates that parameter values obtained on the basis of about ten or more voltage changes (Table 1) can be used for load modelling under similar loading conditions and that reliable parameters are estimated although the nature of load at LV is pretty stochastic. However, in the time interval 18-24 h no large change of voltage occurred and in the interval 6-12 h, on Saturday and on Sunday very small number of changes was recorded, i.e. there was a lack of statistically significant sample of data (or any data). Therefore, a further analysis based on measurements in longer time intervals that will provide more relevant data in all time intervals and all days of the week, will be the subject of the future research. It can also include the determining of the parameters in different months, seasons and years.

Measurements in long time intervals also enable us to adjust and to verify the model recursively. This methodology is applied on the second set of data, while the estimated parameters from the first data set are used as initial values. For every subsequent voltage change load model parameters are identified and adjusted. Thus, the old (previously determined) parameter value is adjusted proportionally to the difference between identified and the old value of the concerned parameter, and the new parameter value is obtained. It is used for model validation by calculating the difference between the measured power response to the subsequent voltage change and the corresponding simulated response on the basis of this new value. The model is validated since such differences are less than 5 %: in 7 % of simulations when parameters that are grouped according to the time intervals are adjusted, and in 10 % of simulations when parameters grouped according to days are adjusted. The most of final parameter values are very close to those from Table 2 indicating that the load composition remained almost the same in the period (on days) that belong to the second data set. For example, final parameters of working days are k_{pu}=1.623 and k_{qu}=3.169, while the corresponding parameters from Table 2 are 1.662 and 2.998, respectively.

It should be emphasized that the results presented in this paper are very valuable because they regard concrete, time variable load. The usage of the parameter values from the literature can lead to significant mistakes since these correspond to the load in different country or the region of the same country, with different load composition. Generally, literature does not provide parameters for different time periods of the day and different days of the week. Thus, for residential load in winter, [2], [15], and [10] just list

k_{pu}=1.5 and k_{qu}=3.2, k_{pu}=1.5-1.7 and k_{qu}=2.5-2.6, and k_{pu}=1.761 and k_{qu}=3.656, respectively. When parameters from [2], mean values from [15] and parameters from [10] are used for simulation of 84 measured *P* and *Q* demands analysed in this paper, in approximately 10 %, 20 % and 14 % of the cases the errors are greater than 5 %. Therefore, data from [2] can be treated as adequate for the considered load, but in general, literature data can lead to significant mistakes.

On the other hand, [7] provides the exponential load model parameters of the predominantly residential load at 10 kV in town Niš (Republic of Serbia) for two winter days – Friday and Saturday in three day periods – morning, afternoon and night. These parameters (Table 3) change in narrower ranges than the mean values of parameters from Table 2: k_{pu} belongs to the range from 1.716 to 1.861 and k_{qu} from 2.962 to 3.616. Data from Table 3 is used for simulations of real and reactive power responses that are recorded in TS "Asambair krug" in the corresponding time intervals and days. In 12.5% of cases simulation errors are greater than 5 % proving that the usage of the parameters of the same load class, but obtained at different voltage level, in different town, and several years before, can cause unacceptable mistakes.

Table 3 Exponential load model parameters [7]

Time interval	Morning		Afternoon		Night	
Day	Friday	Saturday	Friday	Saturday	Friday	Saturday
k_{pu}	1.716	1.791	1.767	1.812	1.861	1.774
k_{qu}	3.565	3.616	3.135	3.169	2.962	3.138

Load modelling procedure demonstrated in this paper can be broadly used in "Elektrodistribucija Vranje" and other utilities equipped with the devices described in this paper or similar recording devices. By now, approximately 200 recording devices similar to the device described in the paper, have been installed in Serbian utility companies. Thus, the procedure based on continuous measurements will allow for the obtaining of load model parameters in different regions of the country and of different load classes. Additionally, the estimated load model parameters can be obtained in different months and seasons, but also for both small and large voltage variations separately.

6. Conclusion

The paper presents simple and efficient load modelling procedure that enables tracking model parameters at low voltage in a long time period. It uses the data from the previously installed recorded device and the measuring information system, stored in central server in the Control centre. In this way additional costs for generally expensive equipment are avoided and easy data access is enabled. Identified parameters are grouped according to day periods and days of the week and the statistically analysed providing parameter estimates proved to be reliable for the load with significant stochastic changes. The estimated values of k_{pu} and k_{qu} vary approximately from 1.4 to 2 and from 2.4 to 3.7, respectively, depending on the period of the day and indicating the changes of load composition. The variations parameter estimates are greater in day periods than in days of the week. The described load modelling procedure can be applied simultaneously at numerous low voltage buses in a long time period providing parameter estimates in different months and seasons valuable for both exploitation and planning purposes.

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